Low pump power co-fiber remotely pumped EDFA used in DWDM systems with ultra-long fiber span

Fan Zhang (张 帆), Wei Zhang (张 巍), Yan Wang (王 燕), and Jiangde Peng (彭江得)

Electronic Engineering Department, Tsinghua University, Beijing 100084

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In this paper, aiming at practical dense wavelength division multiplexing (DWDM) system with ultra-long fiber span, a simple co-fiber remotely pumped erbium-doped fiber amplifier (RP-EDFA) scheme is proposed to extend span distance with simple configuration and low pump power. Equivalent noise figure of −6 dB is achieved under 300-mW pump power. Using the experiment results, numerical simulation of ultra-long span systems shows that for a 40 × 11.6-Gb/s transmission system, the RP-EDFA scheme can support transmission of 1760 km with a fiber span of 160 km. These results demonstrate the potential of the PR-EDFA scheme in ultra-long span transmission.

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Extending span distance is an important way to reduce the cost of long-haul dense wavelength division multiplexing (DWDM) systems. In traditional DWDM systems based on erbium-doped fiber amplifiers (EDFAs), span distance is about 80—100 km. Quantum limitation in noise figure (NF) of EDFAs (3 dB) prevents further extension of span distance with acceptable costs on transmission distance, capacity, and performance. Distributed fiber Raman amplifiers (DFRAs) have been proven to have better noise performance, providing a possible way to support longer fiber span[1]. But watt-class pump light is needed in DFRAs, increasing the costs of system operation and maintenance largely. How to achieve long span distance with a safe pump power is a problem that must be solved in commercial long fiber span systems.

Co-fiber remotely pumped EDFA (RP-EDFA), which combines EDFA and backward pumped DFRA (B-DFRA) in a single transmission fiber, is widely used in long distance repeaterless-systems[2]. Recently, much attention has been paid to applications of RP-EDFA in long-haul DWDM system[3−5], showing that its excellent noise performance is suitable for requiring ultra-long span distance. In these works, complicated PR-EDFA configuration and watt-class pump power were used to pursue the best system performance, and the requirements of the costs of system operation and maintenance in commerce were neglected. In this paper, a simple RP-EDFA scheme is proposed to extend span distance with low pump power. The noise performance of the RP-EDFA scheme is demonstrated experimentally and theoretically. System simulations using this results are taken to show its potential in commercial DWDM systems with ultra-long fiber span.

Figure 1 shows the experimental setup. The fiber span includes a spool of transmission fiber (40 km) and two variable optical attenuators (VOAs). The fiber is long enough to experimentally simulate the B-DFRA after the RP-EDFA. Since only the loss of the rest of the fiber span needs to be considered in the experiment, the two VOAs are used to replace real fibers, providing flexibility to change the location of RP-EDFA. The pump light at 1475 nm is injected to the signal output end of the 40-km real transmission fiber by a $14xx/15xx$ wavelength division multiplexer (WDM). RP-EDFA is inserted between the two VOAs, including a piece of erbium-doped fiber (EDF) (7.5 m) and an isolator (ISO) at the signal input end of the EDF. The ISO is used to reduce the multi-path noise generated by double Rayleigh scattering. Two 1:99 couplers are used to monitor the attenuations of VOAs and the performance of RP-EDFA. A 1552.7-nm distributed feedback (DFB) laser provides the saturation signal of RP-EDFA. A wavelength-tunable laser provides the probe signal. Saturation signal and probe signal are mixed by a 1:9 coupler. The gain and noise performances are measured by an optical spectrum analyzer (OSA, Agilent 86142B).

Firstly, the noise performance is measured. Here, we look the PR-EDFA and DFRA as a lump amplifier at the output end of the fiber span. The NF of the lump amplifier is defined as the equivalent noise figure (NF_{eq}) of the RP-EDFA scheme, calculated by

$$NF_{eq} = \frac{P_{ASE,all}}{h\nu B_0} \times \frac{1}{G_{EDF} \times G_{Raman}}, \qquad (1)$$

where B_0 is optical bandwidth, G_{EDF} and G_{Raman} are the gain of RP-EDFA and the on-off gain of B-DFRA respectively. $P_{ASE,all}$ is the total amplified spontaneous emission (ASE) power at output end of fiber span.

The experiment results of the NF_{eq} are shown in Fig. 2. The fiber span is 200 km. Pump power of RP-EDFA is 300 mW. 40 signal channels (3 dBm/channel) are considered. The NFs of RP-EDFA at three signal wavelengths

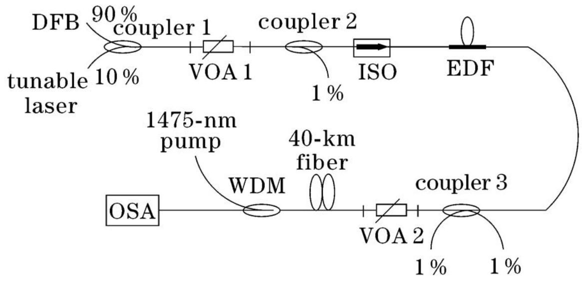

Fig. 1. Experimental setup.

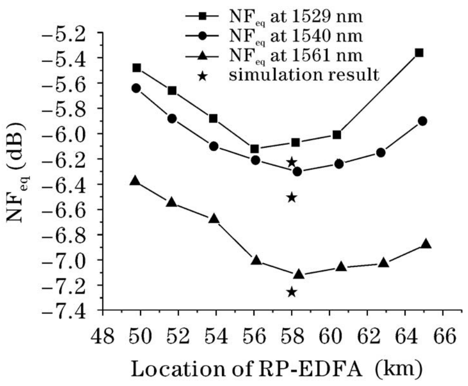

Fig. 2. Experiment and simulation results of gain and noise performance of the RP-EDFA.

(1529, 1540, and 1561 nm) are measured respectively at different locations of RP-EDFA.

Figure 2 shows that there is the best NF according to an optimal location of the RP-EDFA at each curve of different wavelengths. If the location is too far from the output end of fiber span, pump power entering the EDF is weak; if it is too close, signal level is too low to be competed with ASE noise. On the other hand, the NF at 1529 nm is always the worst in the three wavelengths, whatever the location of the RP-EDFA is. So the optimization of the RP-EDFA should be taken according to the result of 1529 nm. In Fig. 2, the optimal location of the RP-EDFA is 56—58 km and the NF_{eq} of the worst channel is about −6 dB. We also numerically simulate such scheme, finding that the optimal location is 58 km. The optimized simulation results, also shown in Fig. 2, are in good agreement with the experiment results. RP-EDFA is simulated by Giles model[6], Raman amplification is modeled by coupled differential equations[7]. All parameters in the simulation are listed in Table 1.

Figure 3 shows the output signal spectra when the location of RP-EDFA is 56 km. Gain spectra of RP-EDFA and B-DFRA are also shown as subplots. The solid and dashed lines represent experiment and numerical simulation results respectively. The simulation agrees well with the experiment result in the shapes of the output signal and gain spectra. The difference in values is within 2 dB, coming from the un-expecting experiment conditions such as loss of fused points and fiber connectors. The uneven shape of the output signal spectrum indicates that a gain-flattening filter is necessary at the end of the transmission fiber in real applications.

To demonstrate the potential of the RP-EDFA scheme in long fiber span DWDM system, system simulations are taken, as shown in Fig. 4. The gain and noise performances of the RP-EDFA scheme use the experiment results with 300-mW pump power. A wideband gain-flattening filter is introduced to flatten the signal output spectrum of the RP-EDFA in each span. Two EDFAs are used to compensate the rest losses of the fiber span and the dispersion compensation fiber (DCF), which are inserted between the two EDFAs. NFs of both EDFAs are 6 dB. In each span, the dispersion is compensated

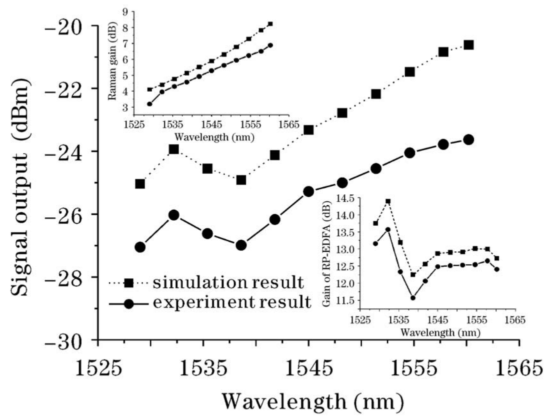

Fig. 3. The signal output spectra of RP-EDFA.

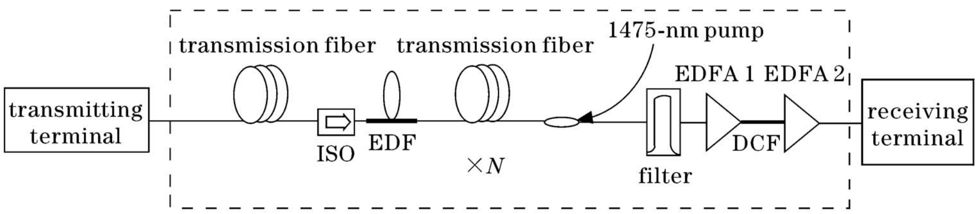

Fig. 4. Configuration of transmission system in simulation.

Table 1. Parameters in Simulation

Transmission Fiber		EDF		DCF	
Loss at 1475 nm	0.253 dB/km	Absorption Coefficient at 1530 nm	5.81 dB/m	Loss at 1550 nm	0.5 dB/km
Loss at 1550 nm	0.225 dB/km	Emission Coefficient at 1530 nm	5.55 dB/m	Nonlinear Coefficient	0.0057 (W·km)$^{-1}$
Peak Raman Coefficient	0.51 (W·km)$^{-1}$	Absorption Coefficient at 1480 nm	2.54 dB/m	Dispersion Coefficient	−85 ps/(nm·km)
Nonlinear Coefficient	0.0012 (W·km)$^{-1}$	Emission Coefficient at 1480 nm	0.8 dB/m	—	—
Dispersion Coefficient	17 ps/(nm·km)	Background Loss	0.006 dB/m	—	—

by DCF totally, and the post dispersion compensation is optimized. Maximal signal power in DCF is lower than −6 dBm/channel (parameters of transmission fiber and DCF are listed in Table 1). The net gain of each span is 0 dB. 40 signal channels spaced by 100 GHz in C band are considered. Line rate is 11.6 Gb/s for each channel, with 16.5% overhead forward error-correction (FEC) code. The signal modulation format is return-to-zero (RZ) with 33% duration. The least requirement of Q value is 8.6 dB.

Figure 5 shows the average Q value of the RP-EDFA based transmission system in three cases. In the case with a fiber span of 160 km and signal power of 3 dBm/channel, the RP-EDFA scheme can support a transmission distance of 1760 km if we set the transmission threshold as 13 dB (4.4 dB margin of Q), with only 300-mW pump power. In the case with 160-km fiber span and signal power of 0 dBm/channel, transmission of 1600 km can be achieved. Only about 1-dB difference of Q value between the two 160-km cases shows that

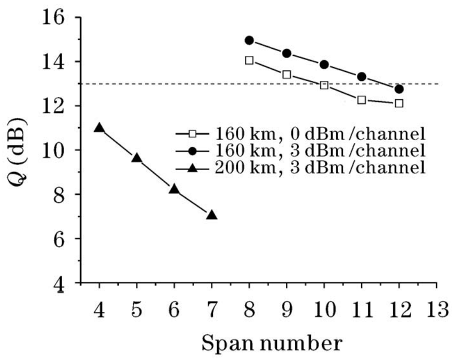

Fig. 5. Q value versus the span number. Uncorrected bit error rate BER $= 4.15 \times 10^{-6}$.

obvious effect of fiber nonlinearity has occurred when signal power changes from 0 to 3 dBm/channel. In the case with a fiber span of 200 km and signal power of 3 dBm/channel, after 4 spans the Q value is decreased to 11 dB (2.4-dB margin), showing that 200-km span is difficult to achieve with the simple RP-EDFA scheme.

In this paper, aiming at practical DWDM system with ultra-long fiber span, a simple co-fiber RP-EDFA scheme is proposed to extend span distance with simple configuration and low pump power. Equivalent NF of −6 dB is achieved in experiments under 300-mW pump power, proving its good noise performance. The potential of the PR-EDFA scheme in long fiber span transmission is demonstrated by system simulation, showing that for a 40×11.6 Gb/s transmission system, the RP-EDFA scheme can support transmission of 1760 km with a fiber span of 160 km.

F. Zhang's e-mail address is zhang-f02@mails.tsinghua.edu.cn.

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